NUMERICAL INVESTIGATIONS IN THREE-DIMENSIONAL INTERNAL FLOWS

SEMI-ANNUAL STATUS REPORT

1 JANUARY THROUGH 30 JUNE 1992

Prepared for:

NASA-AMES RESEARCH CENTER

MOFFETT FIELD, CA 94035

UNDER NASA GRANT

NCC 2-507

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I. BACKGROUND

NASA has an ongoing interest in supersonic and hypersonic inlet flowfield research. Their research efforts are intended to complement prospective aerospace vehicles, such as the High-Speed Civilian Transport (HSCT) and the National Aerospace Plane (NASP), as well as other variants of these vehicles intended for use with air-breathing propulsion systems. Computational Fluid Dynamics (CFD) is expected to be a large player in the design and analysis of such aircraft because experimental facilities are limited. The purpose of this Grant is to apply, evaluate and validate CFD tools for use in high-speed inlet flowfields.

In previous efforts under the current Grant, a two-dimensional full Navier-Stokes (FNS) code (SCRAM2D) was used in a design process that involved parametric modifications of the inlet geometry to arrive at what appeared to be an optimum inlet flowfield that produced a uniform flow at the exit in a very short distance. In these previous studies, the technologies for determining the contours with a "man-in-the-loop" approach for both the ramp and cowl of the inlet were demonstrated and nearly shock-free exiting flowfields were shown to be obtainable. The resulting two-dimensional compression contours were then used with swept sidewalls to form a three-dimensional inlet. Then the three-dimensional Navier-Stokes code (SCRAM3D) was used to investigate the inlet's three-dimensional flow.

One of the major difficulties encountered in the previous studies was that associated with the relatively long time required to obtain a solution using even the 2D FNS code in the design process. Since one of the goals of high-speed inlet design is to produce inputs to the overall aircraft design in a timely manner, it was proposed for this year's research to examine 2D and 3D viscous flow solver techniques alternative to the FNS codes used to date. Areas of the inlet particularly identified for code speed up are those associated with the forebody and external flow ramp systems of the inlet. In these areas, parabolized, or space-marched, Navier-Stokes codes were proposed to be investigated for their applicability in the design process developed previously. This report describes the results of an investigation into the use of two other codes for analyzing the forebody and inlet ramp systems of high-speed inlets.

II. INTRODUCTION

During the course of the present study, two new codes have been made available for potential use in continuing the design of the high-speed inlets. These two codes are UPS3D and STUFF. Both are presently single-block versions of codes that can be used when the flow behaves in a nominally parabolic manner. The UPS code is a parabolized Navier-Stokes code (PNS), developed and used by Scott Lawrence at NASA's Ames Research Center. The STUFF code is a space-marched, thin-layer Navier-Stokes code developed and used by Greg Molvik of the MCAT Institute at Moffett Field, California. The latter code is one that has both space-marched (STUFF) and time-marched (TUFF) versions. The space-marched version and the UPS3D code are conceptually similar and have computer time requirements that appear to be similar.

In the present study, the 2D versions of these two codes have been applied to the Lewis Mach 5 inlet to validate them for use in computing forebody and ramp flowfields and to provide inflow starting conditions for the internal flowfield, which is assumed to be done with an elliptical, FNS code such as SCRAM2D, SCRAM3D or TUFF. Boundary layer profiles obtained in the NASA-Lewis Mach 5 inlet model test are used to validate the viscous calculations in the forebody/ramp environment.

III. RESULTS AND DISCUSSION

The UPS3D and STUFF codes were run in their two-dimensional modes for the studies discussed here. Two important variables of the solutions are the grid arrangements used and the existence of a transition location. The forebody (expansion plate) and the three ramps of the Mach 5 inlet were considered first in order to establish the validity of the two codes. Figure 1 shows the comparison between the UPS and STUFF results, run in the 2D mode for a 120 point grid with a grid clustering parameter of β equal to 1.00005. This latter grid spacing parameter controls the logarithmic clustering near the solid surfaces. This value of β produces a highly clustered grid that can resolve sublayer nearwall behavior in the turbulent boundary layer. Both solutions were run assuming a transition from laminar to turbulent flow at the leading edge of the expansion plate. Figure 1 shows the normalized pitot pressure contours obtained from the two solutions. The UPS results are shown to the left side of the figure while STUFF results are shown to the right. In the upper portion of the figure, the actual vertical scale is used. In the lower portion of the figure, the vertical scale has been expanded considerably to show details of the multiple shockwave system. As is clear from Figure 1, the solutions give virtually identical results and both adequately capture the ramp shockwave system. The apparent thicknesses of the ramp shockwaves are seen to increase with increasing distance away from the ramp surface. This increased thickness is due to the one-sided clustering of the grid used here; that is, only near the solid surface of the ramp and expansion plate is the grid clustered. The mesh spacing increases with distance away from the solid surface.

The solutions shown in Figure 1 would be typical for inlet forebody and ramp flowfields, however, they are basically external flows. Of primary interest in the present study is the behavior of the flow in the internal flow portion of the inlet. The application of either the UPS or STUFF code to flows throughout the inlet system, including the cowl, ramp shoulder and throat section, is of interest, although the space-marched codes may produce physically implausible results within the inlet. Figure 2 and Figure 3 show the internal flowfields for these two codes.

Figure 2 shows the results from the UPS code applied on a 2-grid configuration. The upstream grid is the one-sided clustering discussed with respect to Figure 1, while the second grid (from the cowl lip downstream) is clustered on both sides. The β value for this application is the same as for Figure 1. Because of a current restriction in the application of the UPS code to internal flows, the cowl boundary layer can be treated as a laminar flow only. Thus, the cowl boundary layer thicknesses are aphysical with respect to experimental data, but the solution does show the intersection of the cowl shockwave and the ramp boundary layer and the continuation of the solution throughout the inlet passing through the minimum area. It is known, from experimental data and previous FNS solutions of the internal flow portion of the inlet, that without boundary layer bleed on the ramp surface, a separation exists at the cowl shockwave/ramp boundary layer interaction and evolves to an inlet unstart, whereas the space-marched code indicates an aphysical result, showing the inlet to remain started and the solution continuing throughout the inlet.

Figure 3 shows a similar application of the STUFF code to the internal flow portion of the inlet. Here, the grid-clustering parameter has been increased by two orders of magnitude in order to obtain some of the first timings for these codes. The forebody and internal solutions took approximately 100 seconds on a Cray Y-MP to complete, indicating the very rapid calculation capability of the space-marched code. Again, the STUFF code marches through the location of the known separation and unstart condition. For the STUFF results, a turbulent calculation on the cowl is possible and transition from laminar to turbulent flow was assumed to exist at the cowl leading edge. When the grid-clustering parameter was set equal to that in Figures 1 and 2, the solution took much longer, but, as shown in Figure 4, few significant changes occurred in the Mach number contours, although surface quantities such as skin friction and heat transfer would likely be substantially different. Additional run times are about a factor of 8 to 10 larger than the 100 seconds to obtain the additional resolution.

Results presented in Figures 1 through 4 indicate that both UPS3D and STUFF can do a credible job of calculating the forebody flowfields on grids that have the capability to give much higher accuracy than any grids previously used with the full Navier-Stokes code, SCRAM2D. The timing for SCRAM2D to solve the forebody and ramp flows ranges between 2 to 3 hours of Cray Y-MP time on a loosely (β = 1.04) clustered grid. In contrast, either UPS or STUFF can obtain a physically comparable solution in less than 2 minutes. Furthermore, either of the space-marched codes can be used to obtain much higher resolution of the nearwall flows in less than about 15 minutes. They can also be applied in a portion of the internal flow of the inlet upstream of the location of any potential separations. The validity of the solutions coming from either of these codes, particularly with respect to calculating boundary layer properties upstream and downstream of the multiple ramp-shock interactions, is demonstrated in Figure 5. The multiple parts of Figure 5 are comparisons of the UPS and STUFF code solutions with experimental data obtained from the NASA-Lewis Mach 5 experiment. Both CFD solutions were obtained on grids with $\beta = 1.00005$. As can be seen, both codes do an excellent job of predicting the qualitative and quantitative behavior of these pitot profiles, thus validating them for use in the nominally parabolic portion of a high-speed inlet.

Although the application of either UPS or STUFF throughout the internal flow portion of the inlet is of interest, the results are known to be aphysical, and focus must return to the primary use of space-marched codes in inlet analysis and design. This use is to solve the flowfields upstream of the significant elliptical behavior within the inlet. In this sense, the space-marched codes can be used up until boundary layer separation, and/or tendency towards an inlet unstart, becomes evident. At that point, the space-marched results at the last useful plane can be used as inflow conditions to the elliptical full Navier-Stokes time-marched codes such as SCRAM2D or TUFF. The application of a combination of PNS and FNS codes is shown schematically in Figure 6. Here, the Mach 5 inlet Mach number contours are shown for the full inlet using the PNS code in the upper portion. A detail of the internal flow results obtained with the UPS code is shown in the lower left portion of the figure. In the lower right portion of the figure, the inflow plane to

SCRAM2D is taken from the UPS code and solved in a normal manner for the Mach 5 inlet flowfield, including boundary layer bleed applied to the ramp surface to prevent separation. The differences between the UPS PNS results and the SCRAM2D FNS results are clear. The bleed thins the boundary layer in the SCRAM2D code as is known to occur from experiment, the inlet does not unstart and the nominal solution, including the turbulent cowl, is obtained.

Figure 7 shows the detail of this latter solution, in which the UPS code was run initially on a one-sided grid upstream of the cowl lip, then on a double clustered grid with very fine resolution downstream of the cowl lip but upstream of the expected separation region. These two solutions were then followed by the application of a SCRAM2D code, including boundary layer bleed on the ramp surface, throughout the remainder of the inlet. The use of the UPS code near the cowl lip region enhances the sharpness of the cowl shock wave that has been shown to be elusive when using a full Navier-Stokes solver in that region. In this figure, both the UPS solutions were obtained on a very fine grid, while the SCRAM2D solution was obtained on a relatively coarse (β = 1.04) grid used throughout the study of the Mach 5 inlet with the 2D and 3D FNS codes. The computer time involved for this entire solution is only 16 minutes, compared with about 3 hours when using SCRAM2D from the leading edge of the expansion plate through the internal portion of the inlet. The use of a PNS code with its fine grid in the upstream flow also yields a more accurate solution than could be obtained practically with the FNS code alone.

Similar results can be obtained by combining the STUFF and SCRAM2D codes. Figure 8 shows the results of applying the STUFF code in a manner similar to that discussed in Figure 7. In Figure 8, the mesh clustering parameter, β, was reduced in the SCRAM2D code from 1.04 to 1.005, thus increasing the nearwall resolution significantly. Results from using UPS as the upstream code are also shown here. Run times for results shown in Figure 8 are about 2 hours total. However, the nearwall resolution of these FNS solutions is much higher than previously obtained, so that for the same run time as used previously, much better physical resolution is expected. On the other hand, for cases not requiring fine nearwall resolution, solutions may be obtained in much shorter time. It can be concluded that the use of either the UPS or STUFF codes as the upstream flow solver for SCRAM2D is a viable and very economical technique.

IV. CONCLUSIONS

An investigation was carried out into the feasibility of using either of two space-marched Navier-Stokes codes for solving the flow in an inlet system where the flow is behaving parabolically. The two codes, UPS3D and STUFF, were validated here for use in applications to these flowfields based on experimental data for the turbulent boundary layer and examination of the physically realistic multiple shockwave systems produced by each of the codes. The codes have been adapted to produce output files consistent with input files for the elliptical full Navier-Stokes code, SCRAM2D, for continuation of calculation throughout a practical inlet flowfield. Significant time reductions in the calculation have been shown to exist with commensurate increases in nearwall resolution due to the ability to use much finer grids in the flowfield solution. Reductions from run times of the order of 2 hours to run times less than 20 minutes have been demonstrated. This capability is now resident and is planned to be used throughout the remainder of the present investigation.

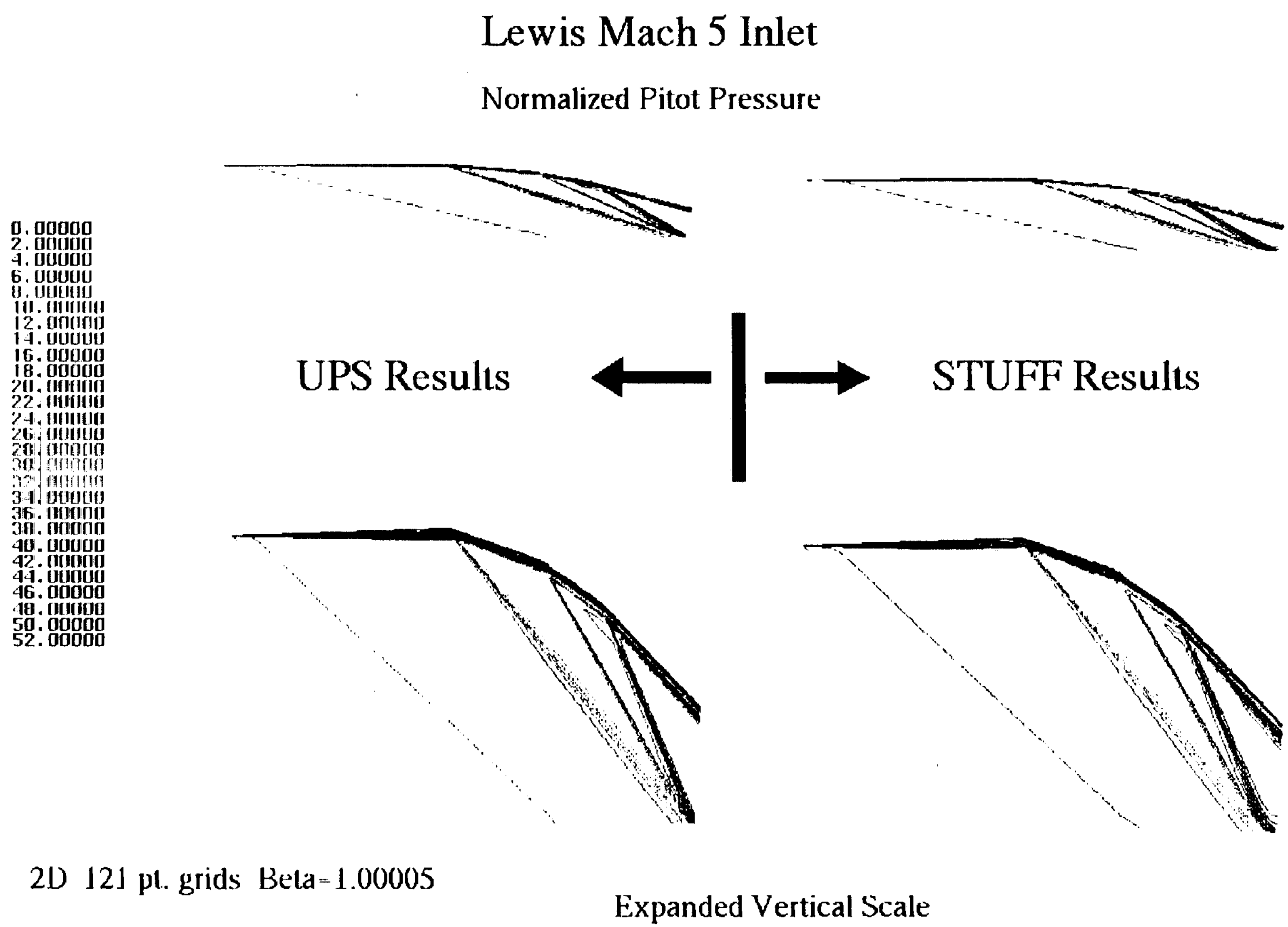

FIGURE 1 **Comparison between UPS and STUFF codes for the Mach 5 inlet forebody and ramp system.**

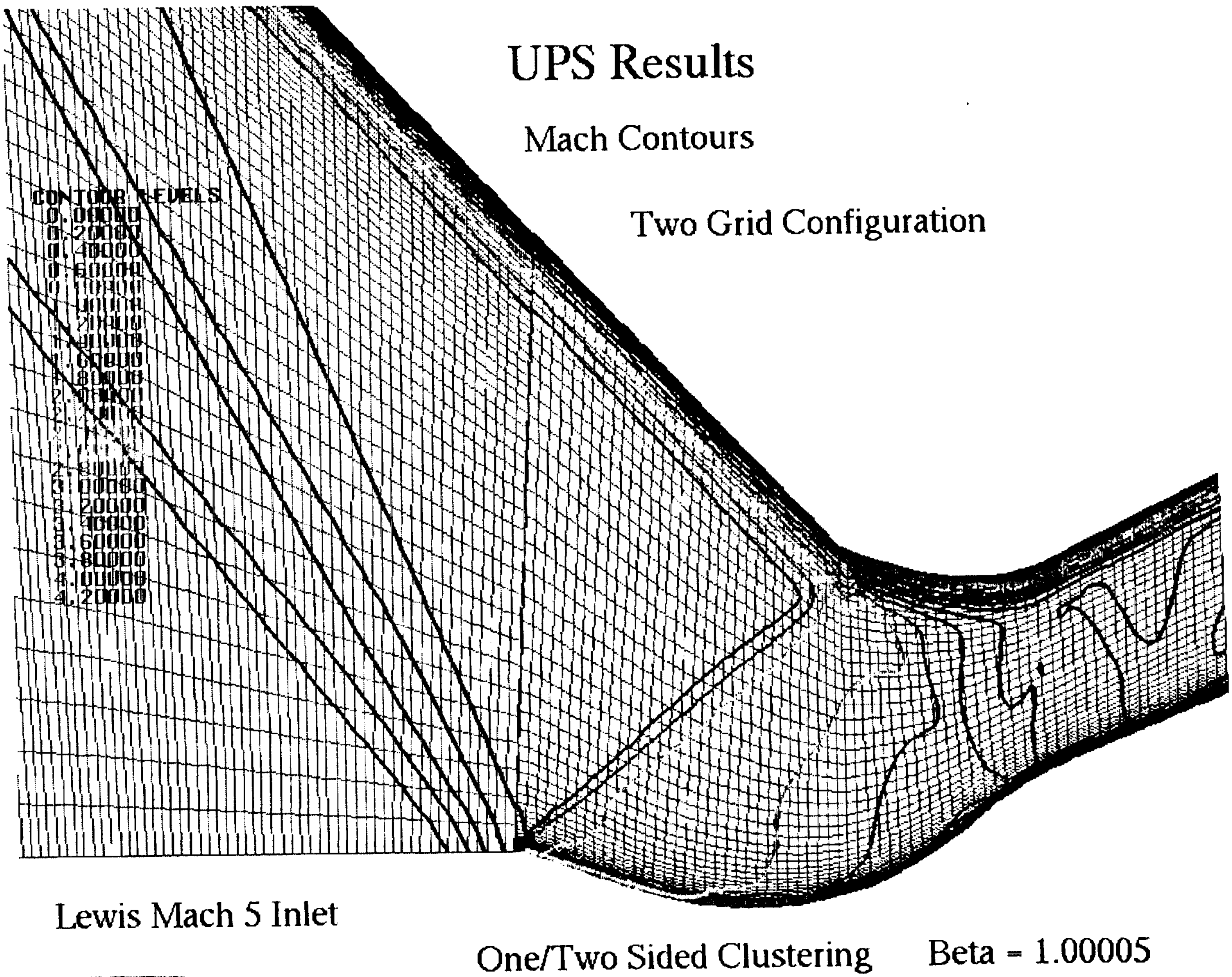

FIGURE 2 **Application of the UPS code to external and internal portions of the Mach 5 inlet.**

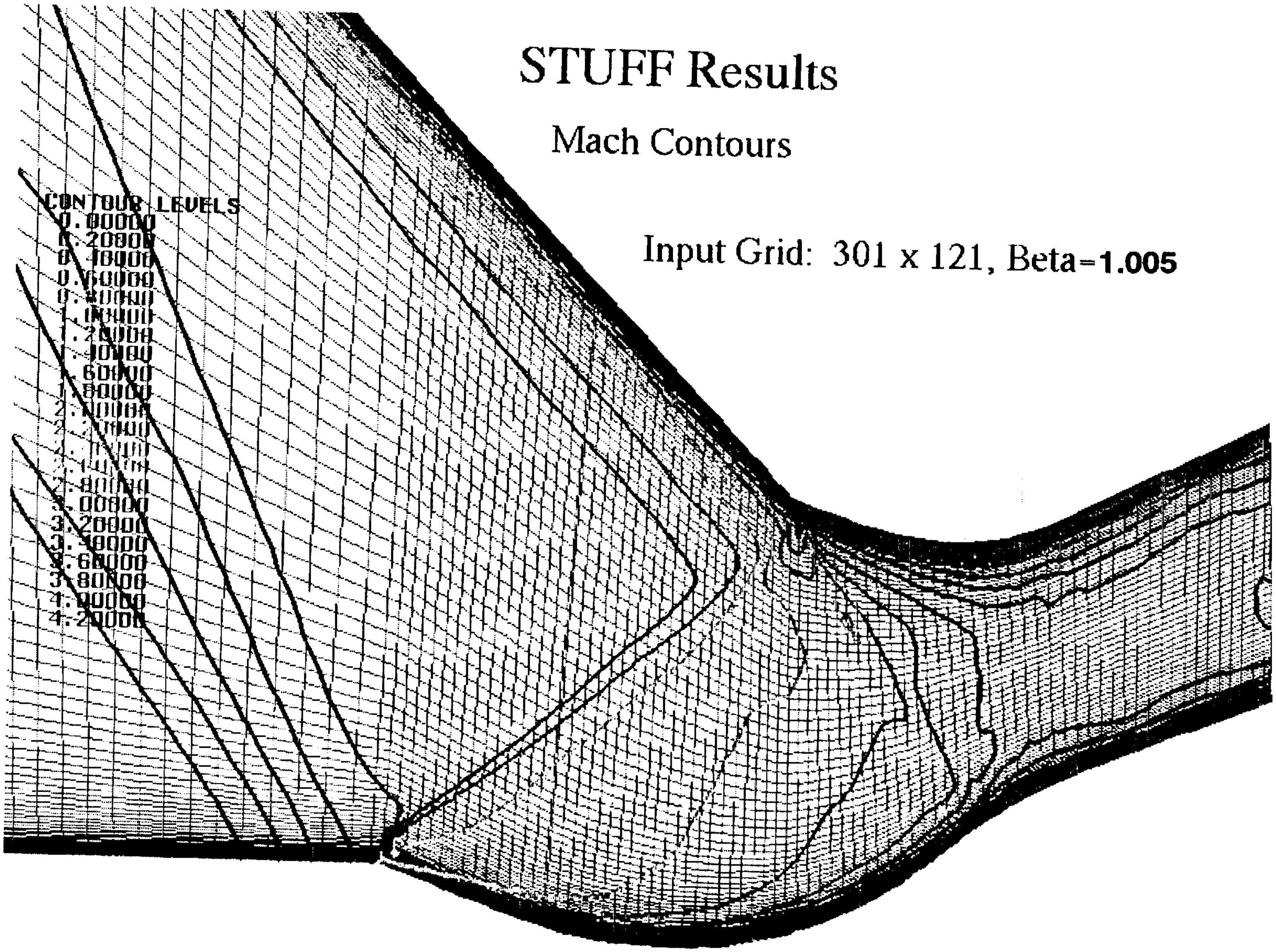

FIGURE 3 **Application of the STUFF code to external and internal portions of the Mach 5 inlet.**

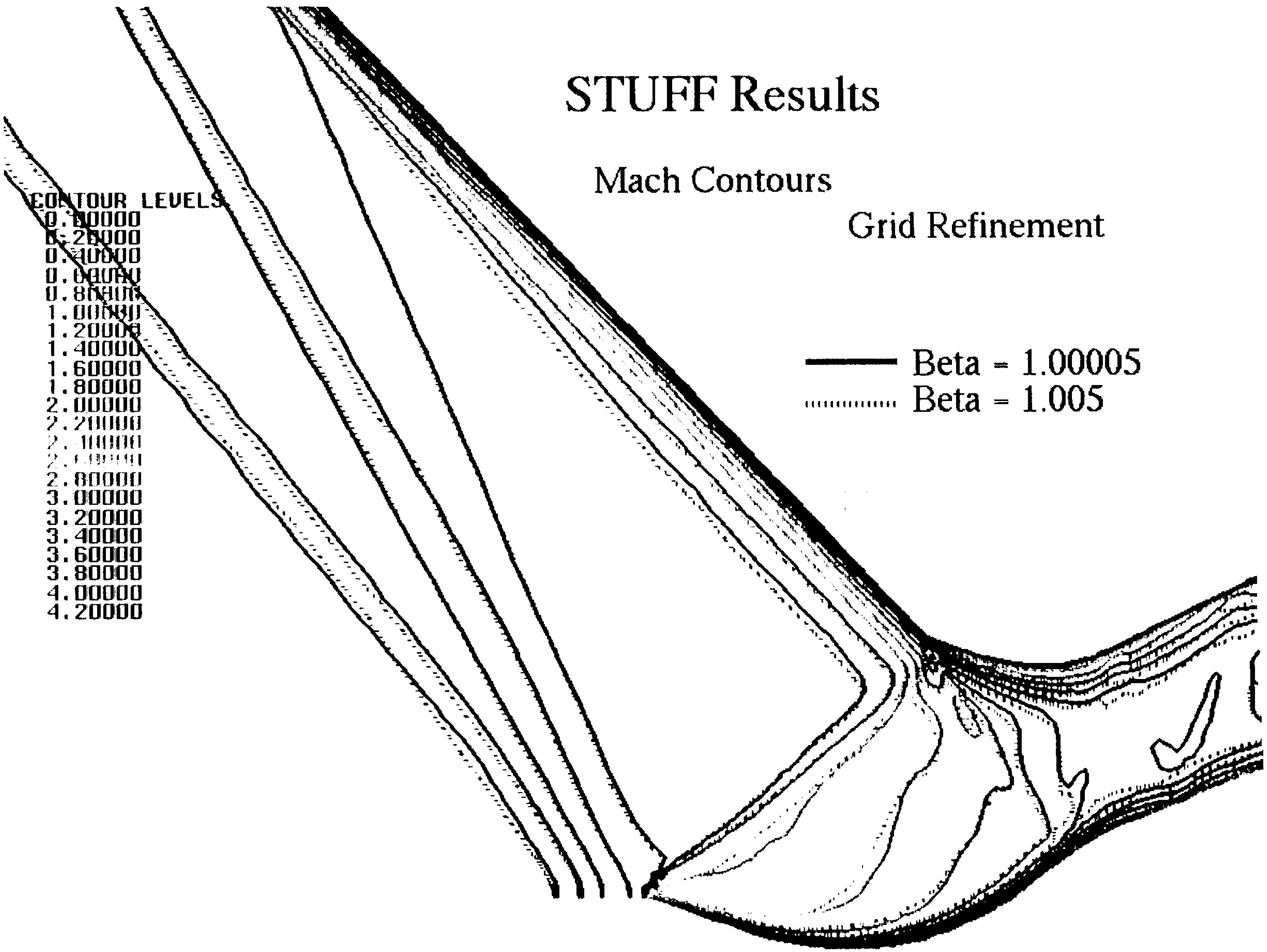

FIGURE 4 Comparison of STUFF results for different grid clustering parameters.

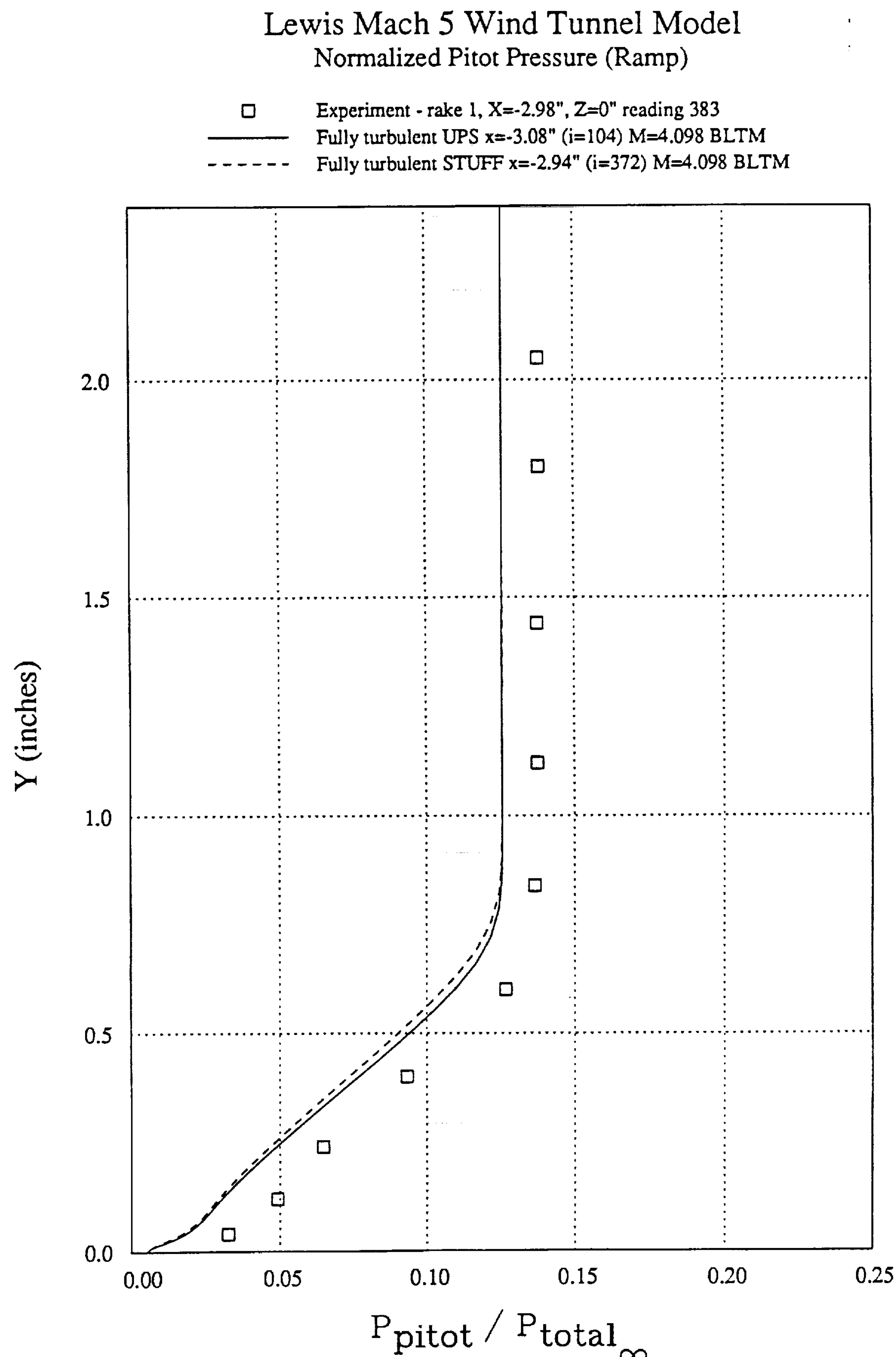

FIGURE 5 Comparison between UPS and STUFF and experimental data boundary layer pitot profiles for the Mach 5 inlet model.

a) x = -2.98"

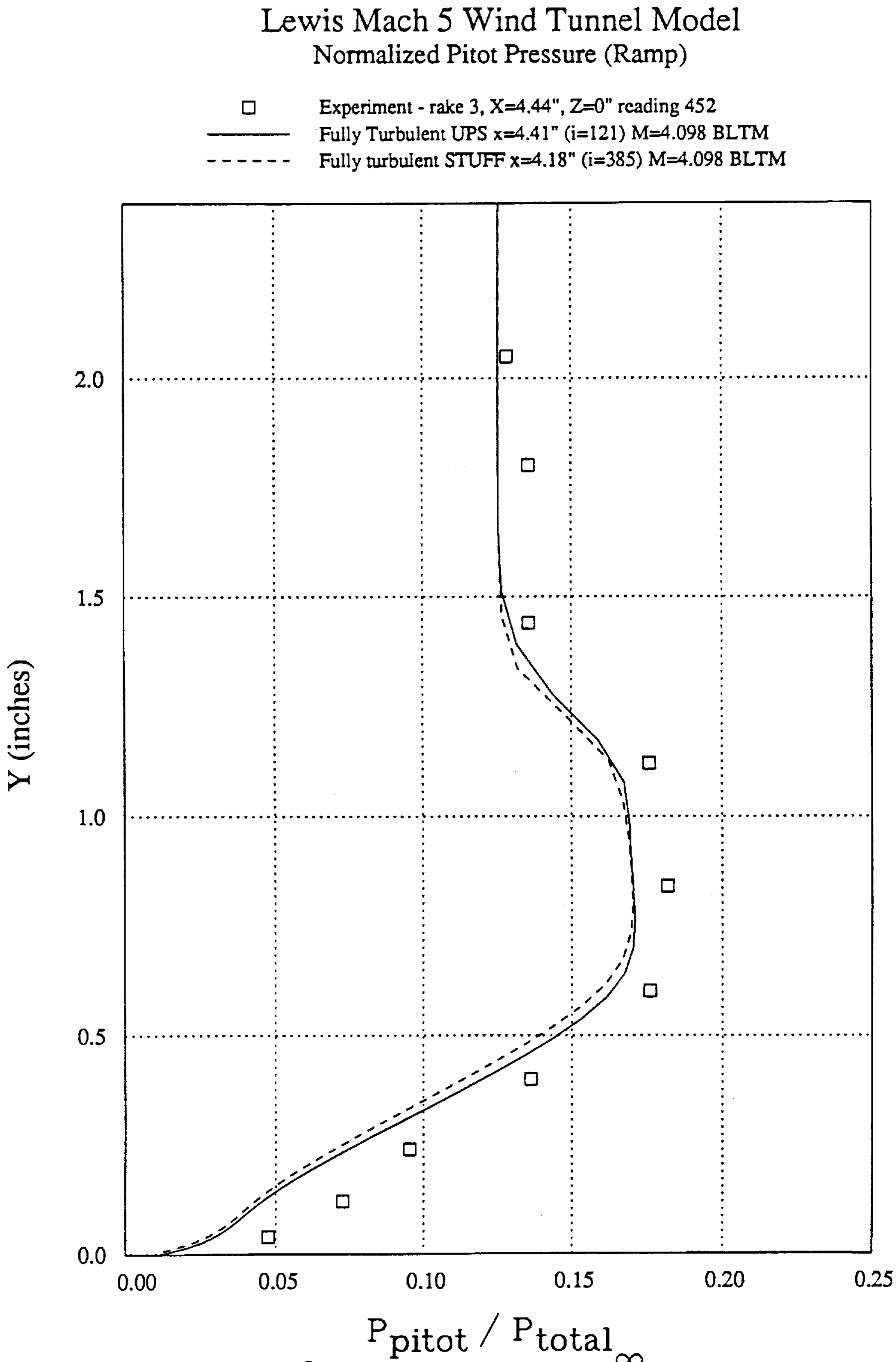

FIGURE 5 Continued.

b) x = 4.44"

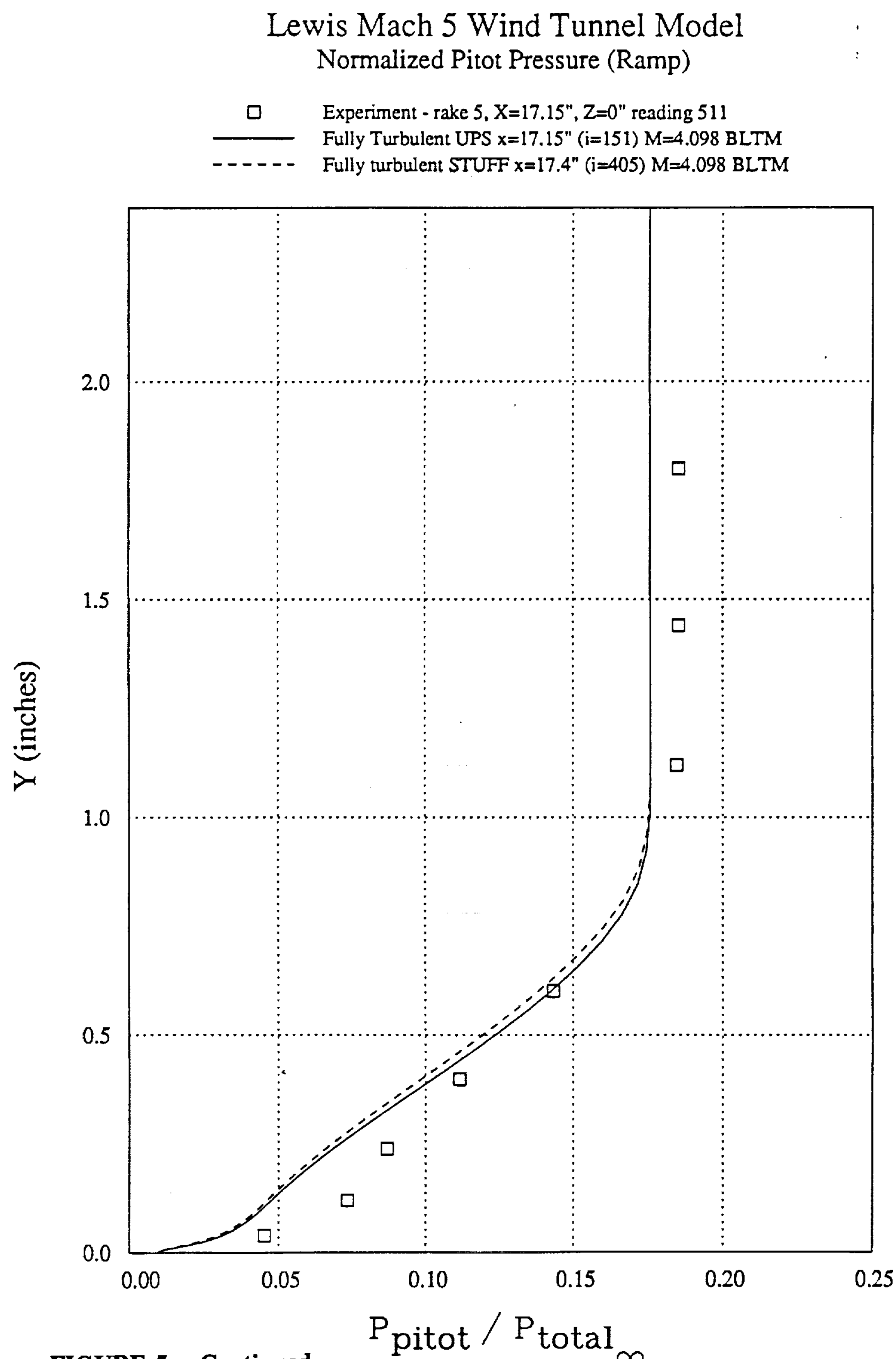

FIGURE 5 Continued.

c) x = 17.15"

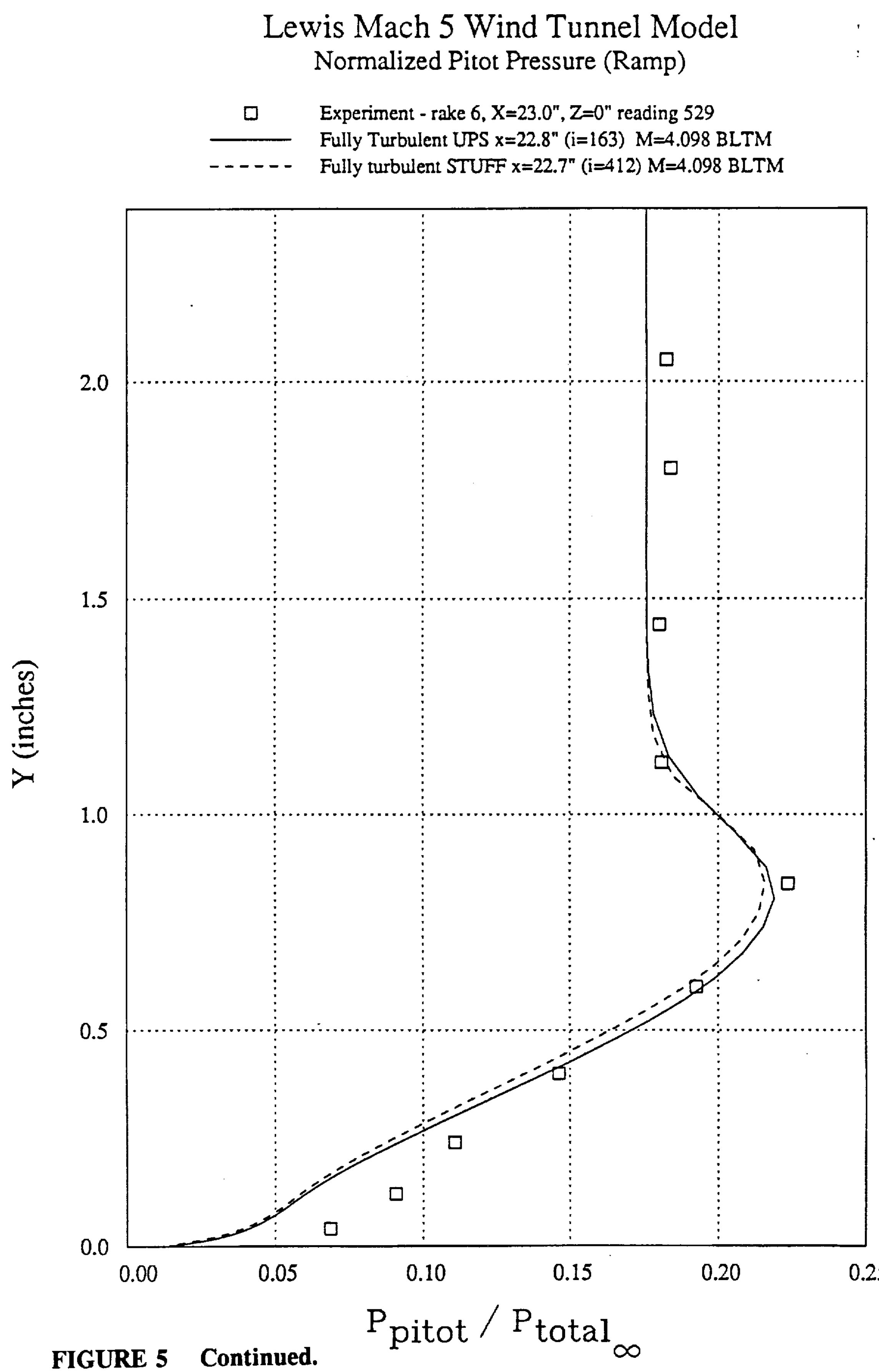

FIGURE 5 Continued.

d) x = 23.0"

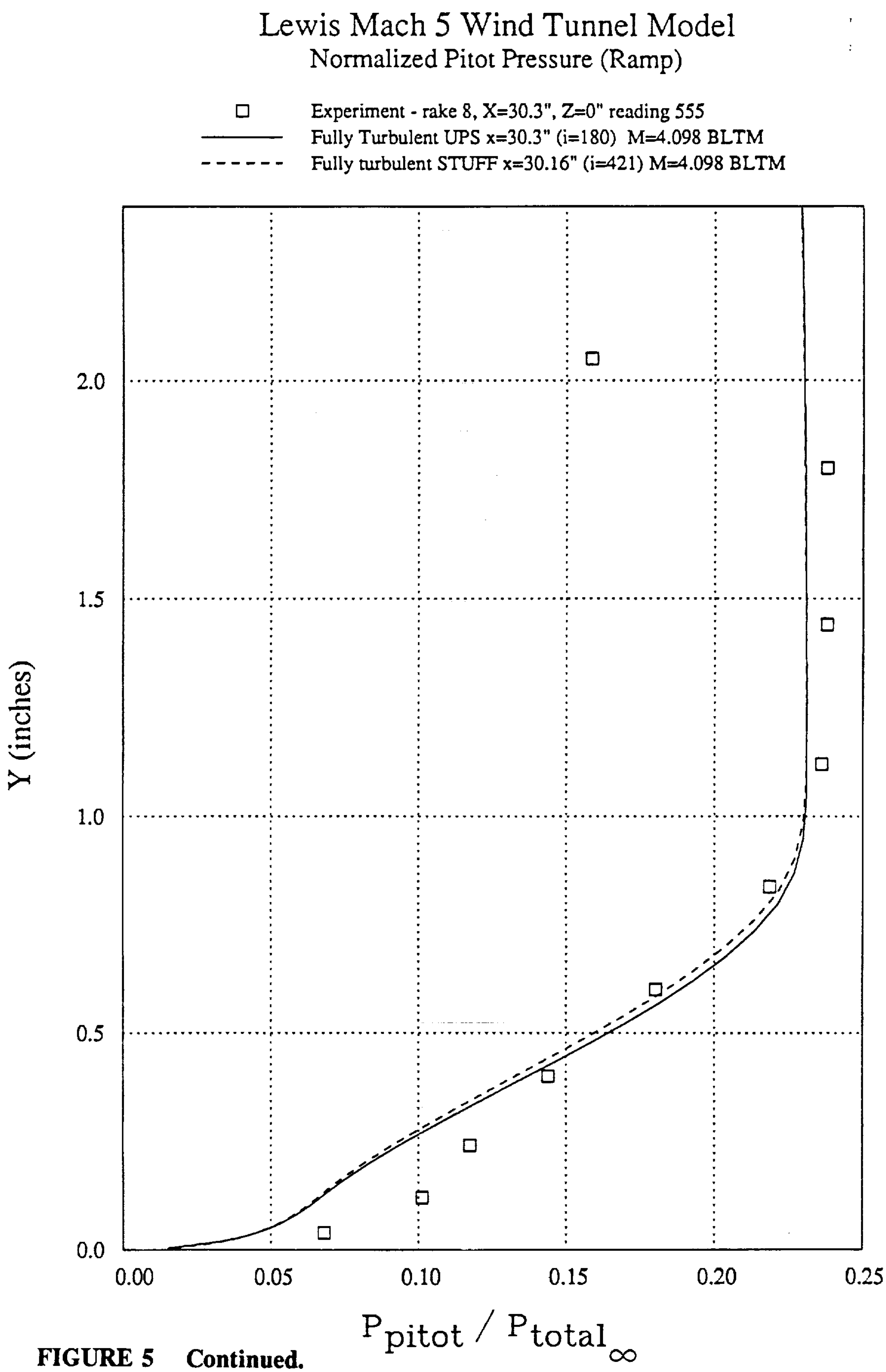

FIGURE 5 Continued.

e) x = 30.3"

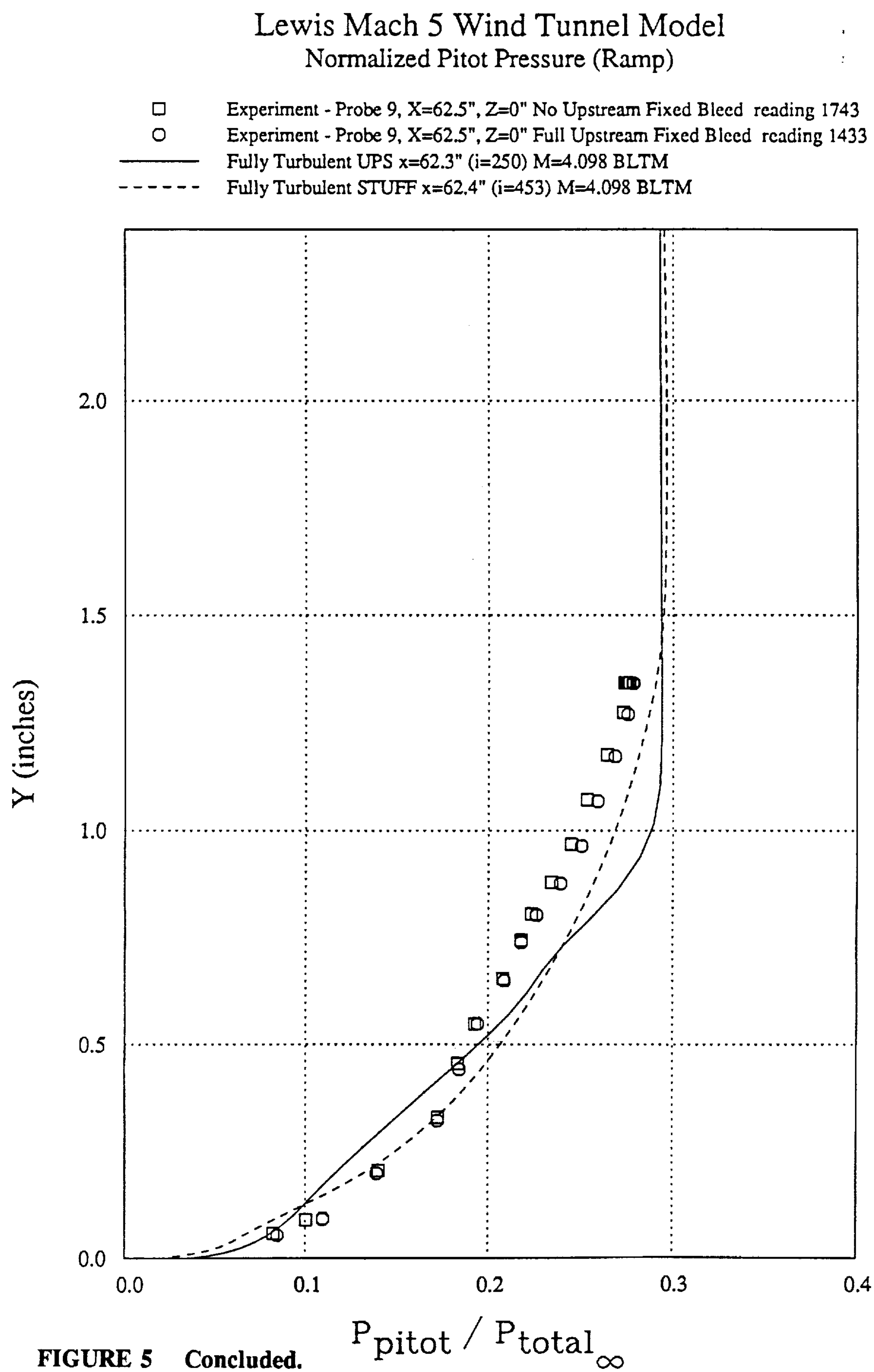

FIGURE 5 Concluded.

f) x = 62.5"

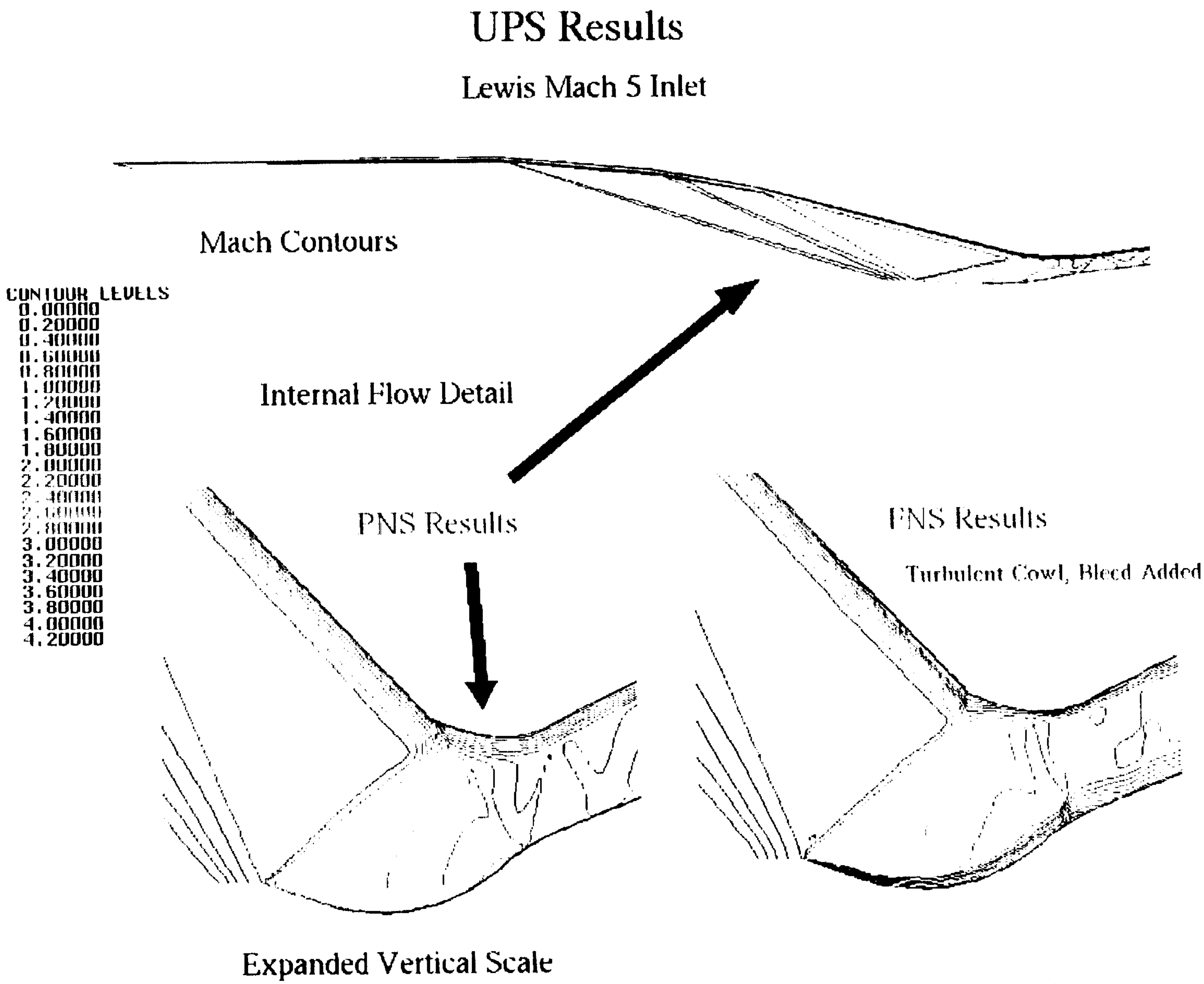

FIGURE 6 **Use of the upstream results from UPS applied as inflow to SCRAM2D code just upstream of cowl lip.**

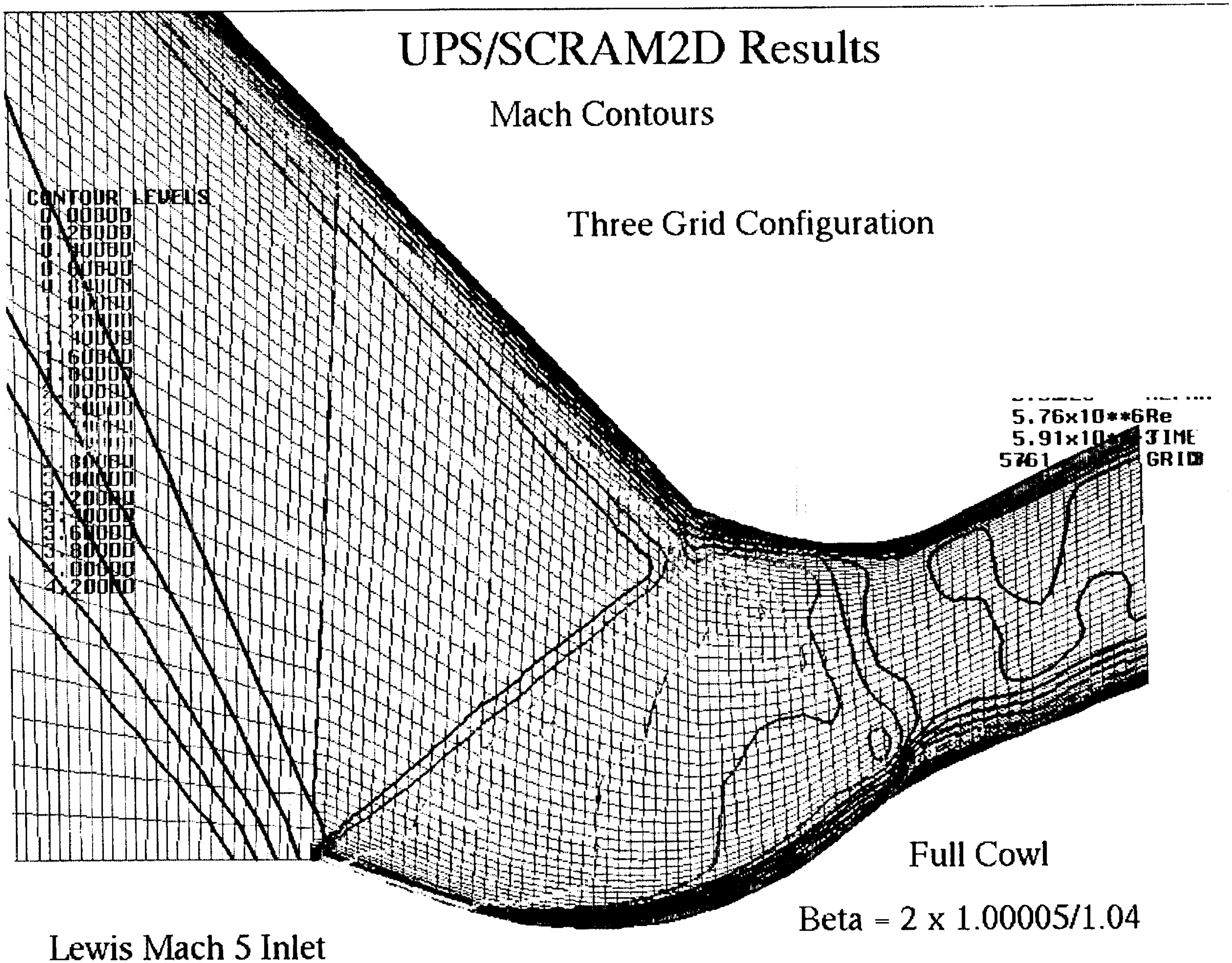

FIGURE 7 Use of the upstream results from UPS applied as inflow to SCRAM2D code downstream of cowl lip.

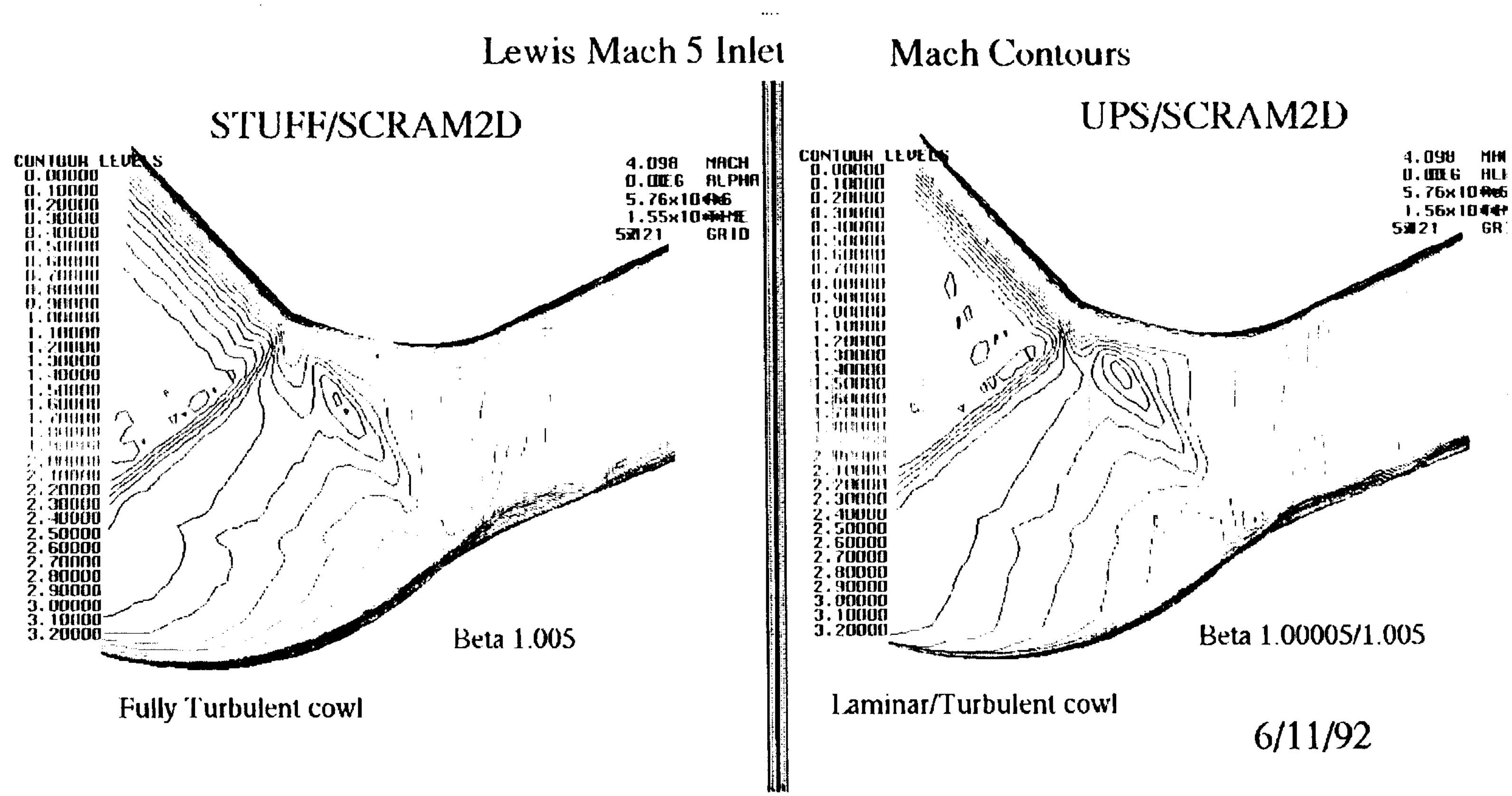

FIGURE 8 **Use of the upstream results from STUFF applied as inflow to SCRAM2D code downstream of cowl lip.**